Broadband Delay and Evolution of the VGOS Network

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Outline

- *Short history of geodetic VLBI given by ARW this morning*
- VLBI2010 (IVS WG3)
  - Drivers
  - Objectives
  - Design
- Implementation on GGAO12M and Westford
- Observation, correlation, and analysis
- Global VGOS network evolution

Special thanks

- Chris Beaudoin, Chris Eckert, Mark Derome – Broadband signal chain design and implementation
- Chet Ruszczyk, Jason Soohoo, Mike Poirier, Katie Pazamikas, Jay Redmond, Russ McWhirter – observing session setup and operation
- Ed Himwich – antenna checkout for GGAO12M and Westford and Field Station modification for Broadband
- John Gipson – *sked* modification
- Mike Titus – correlation (understatement of effort!)
- Brian Corey – station performance analysis and amplitude calibration
- Roger Cappallo – *difx* and *fourfit* modifications
- David Gordon – data base modification and creation
- Sergei Bolotin – *nuSolve* creation and processing
- Bill Petrachenko – brilliant ideas, continued encouragement
- Many others!

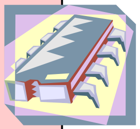
Why do we need a next generation VLBI observing system?

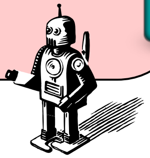
Aging systems (now ~35 years old):

- Old antennas
- Obsolete electronics
- Costly operations
- RFI

Emerging Technology:

- Fast antennas
- Digital electronics
- Hi-speed networks
- Automation





New system

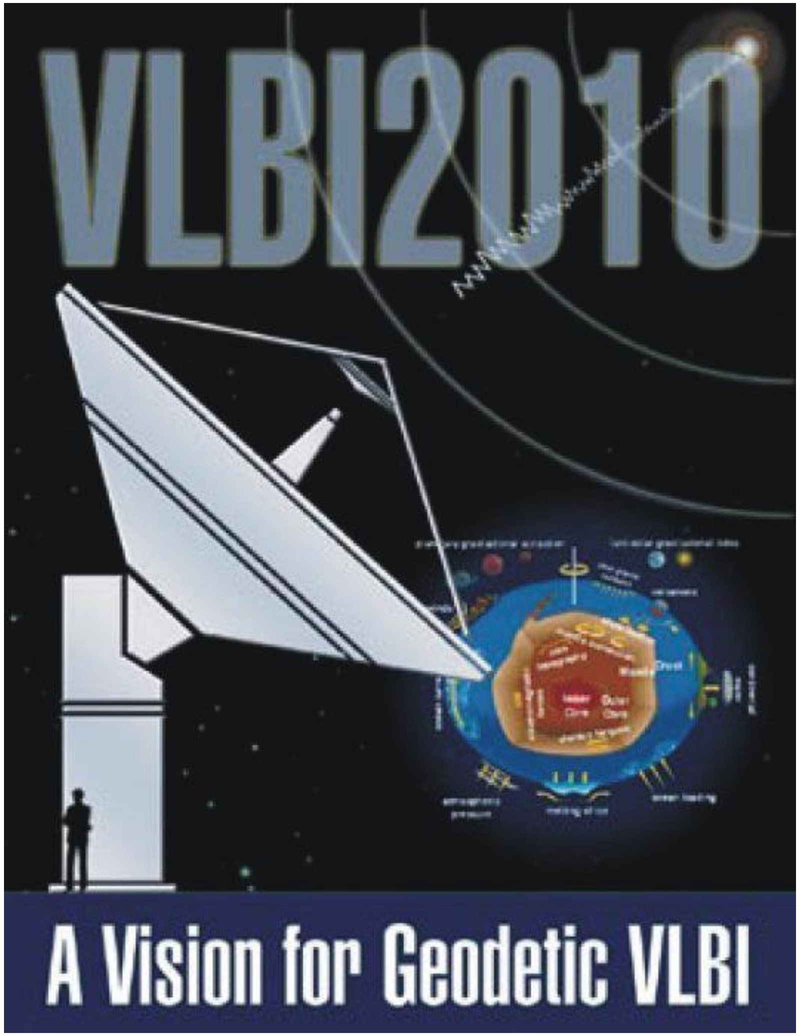
New requirements:

- Sea level rise
- Earthquake processes
- 1-mm accuracy
- GGOS

Courtesy Bill Petrachenko

IVS WG 3 report (2005)

http://ivscc.gsfc.nasa.gov/about/wg/wg3/IVS_WG3_report_050916.pdf



VLBI2010 Recommendations

VGOS Goals

1-mm position accuracy

Need to reduce systematic errors

Acquire many more observations per day by using:

- fast slewing, compact antennas (12°/s Az; 6°/s El)
- short on-source integrations (5-10 sec)
  - very high data rates (16 Gbps or more)
  - new "Broadband" systems to get high delay precision at modest SNR

Continuous measurements of station position and EOP

Reduce operational costs in all areas

- Increase remote control of stations
- Increase automation of both stations and analysis

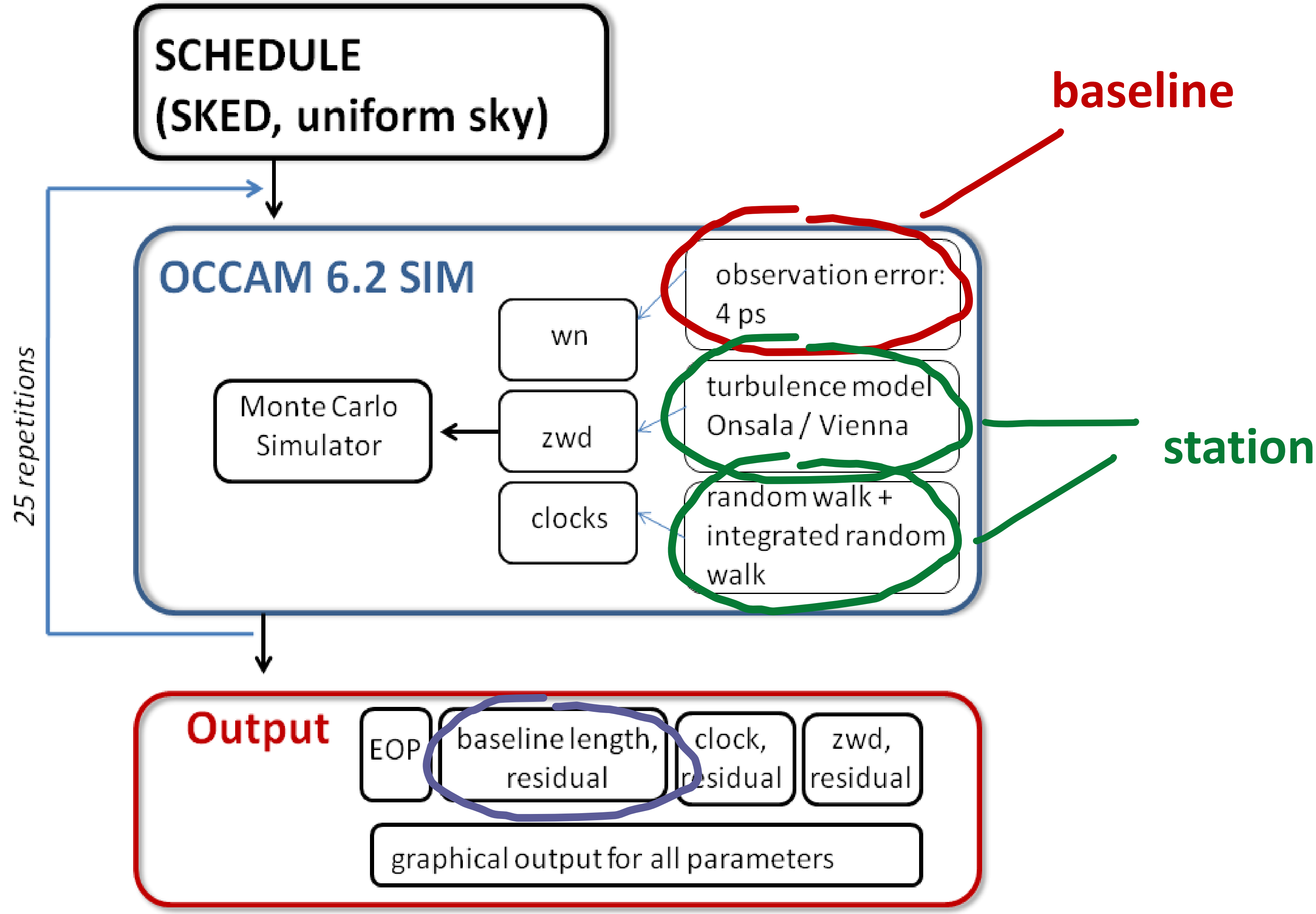
Turn-around time to initial products <24 hours

- e-VLBI wherever possible using improved networks
- Solve last km access issues to more sites

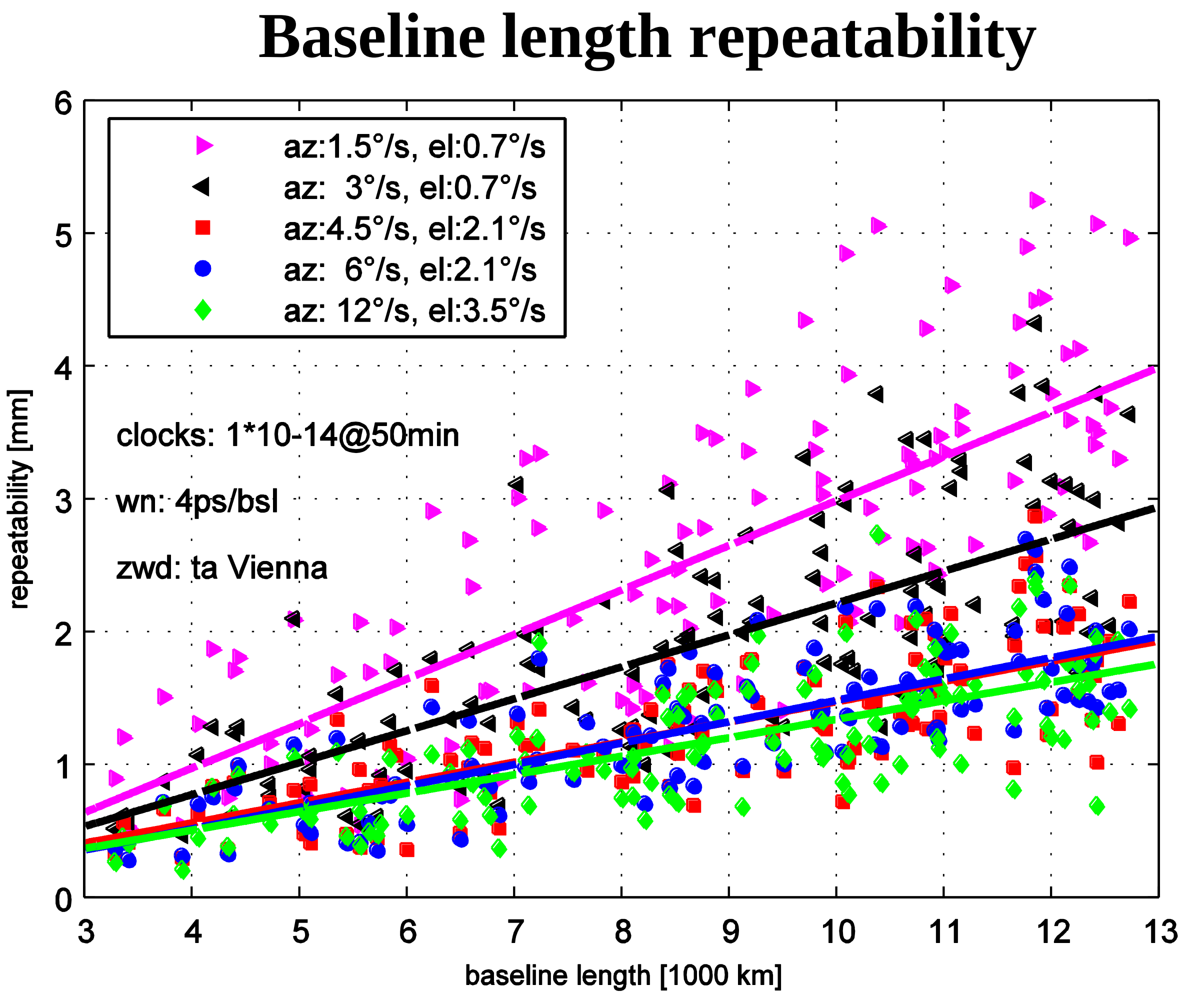
Strive for good global distribution of stations

Courtesy Bill Petrachenko

VLBI2010 – Monte Carlo simulations



Slew speed tests using SKED



16 antennas

zwd:

turbulence model -Vienna

clocks:

$1 \cdot 10^{-14}$@50min

wn: 4psec/bsln

Frequency/antenna issues - 1

- Atmosphere error
  - Increase number of scans per hour
    - Faster antennas ➔ smaller antennas
    - Smaller antennas ➔ lower sensitivity
  - Retrieve sensitivity
    - ➔ Higher data rate
    - ➔ Increase recorded bandwidth
  - Reduce delay uncertainty
    - ➔ Wider spanned bandwidth

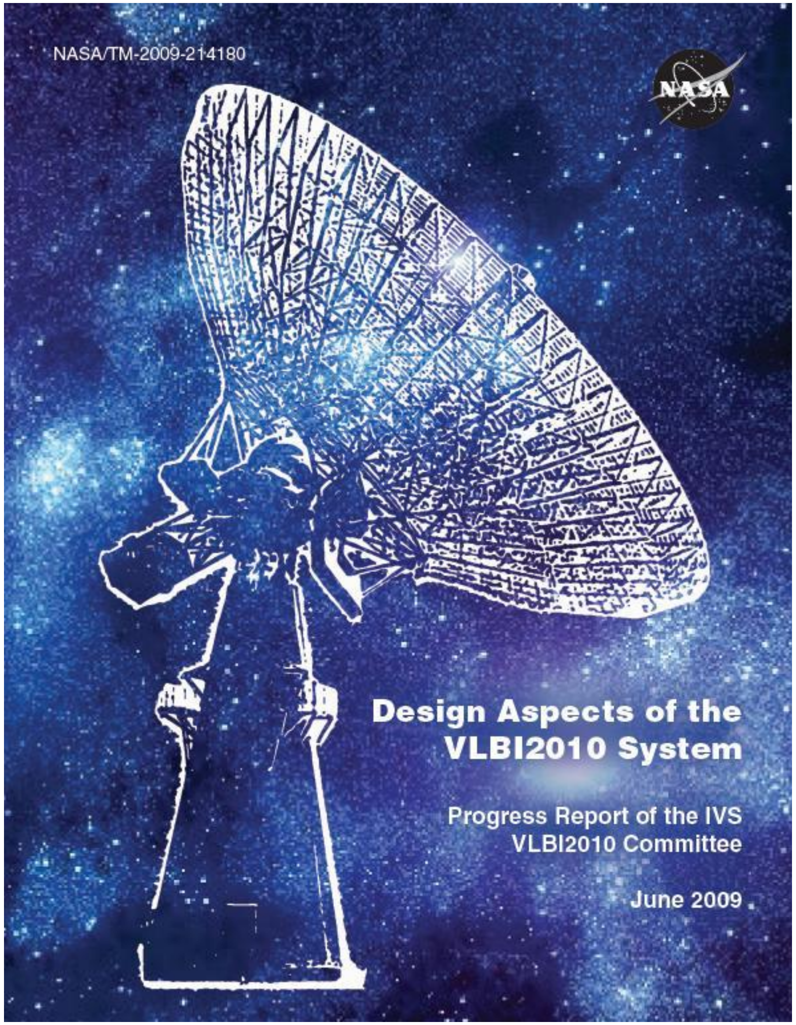
Frequency/antenna issues - 2

- Radio source structure error
  - Desired: use most point-like radio sources
    - Simpler structure → higher frequency
    - Higher frequency → weaker sources
    - → more atmosphere loss and noise
    - → more accurate antenna structure
    - → more expensive
    - → Compromise required on highest frequency to use!

VLBI2010 – V2C Progress Report

- “Design Aspects of the VLBI2010 System”

  ftp://ivscc.gsfc.nasa.gov/pub/misc/V2C/TM-2009-214180.pdf



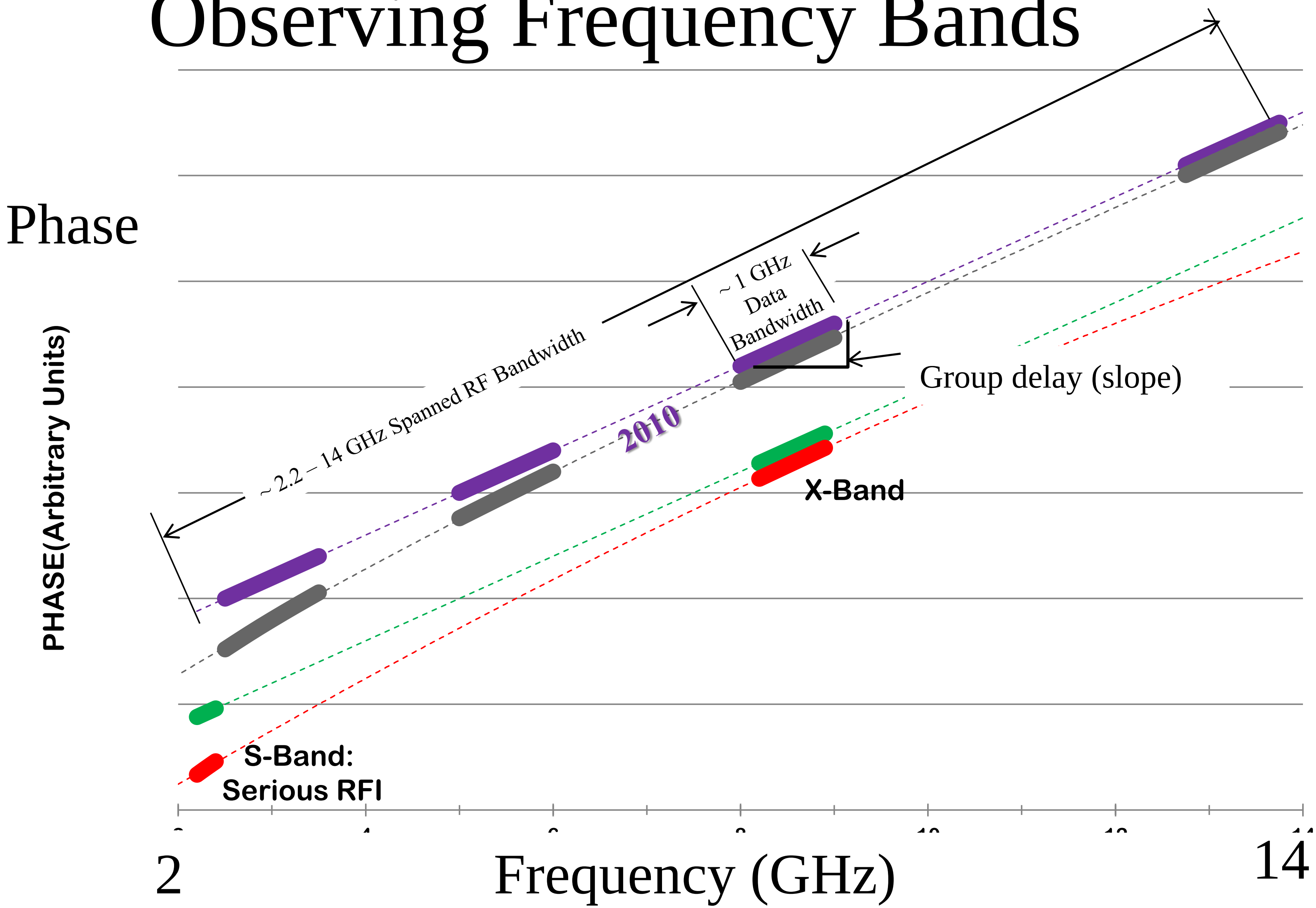
Proposed system characteristics - 1

- Antenna and receiver
  - Frequency range
    - 2.2 to 14 GHz (minimum)
  - Minimum slew speed
    - Azimuth: 12 degrees/sec
    - Elevation: 5 degrees/sec
  - Diameter
    - 12 meters or larger
  - Sensitivity
    - 2500 Jy or less (Tsys less than 50K)

Proposed system characteristics - 2

- Radio frequency and data acquisition
  - Frequency bands
    - Four or more bands
    - Bandwidth 1 GHz each band
  - Frequency agility
    - Require tunability of bands to mitigate RFI
  - Polarization
    - Dual polarization (not necessarily linear)
  - Electronics
    - Digital where possible

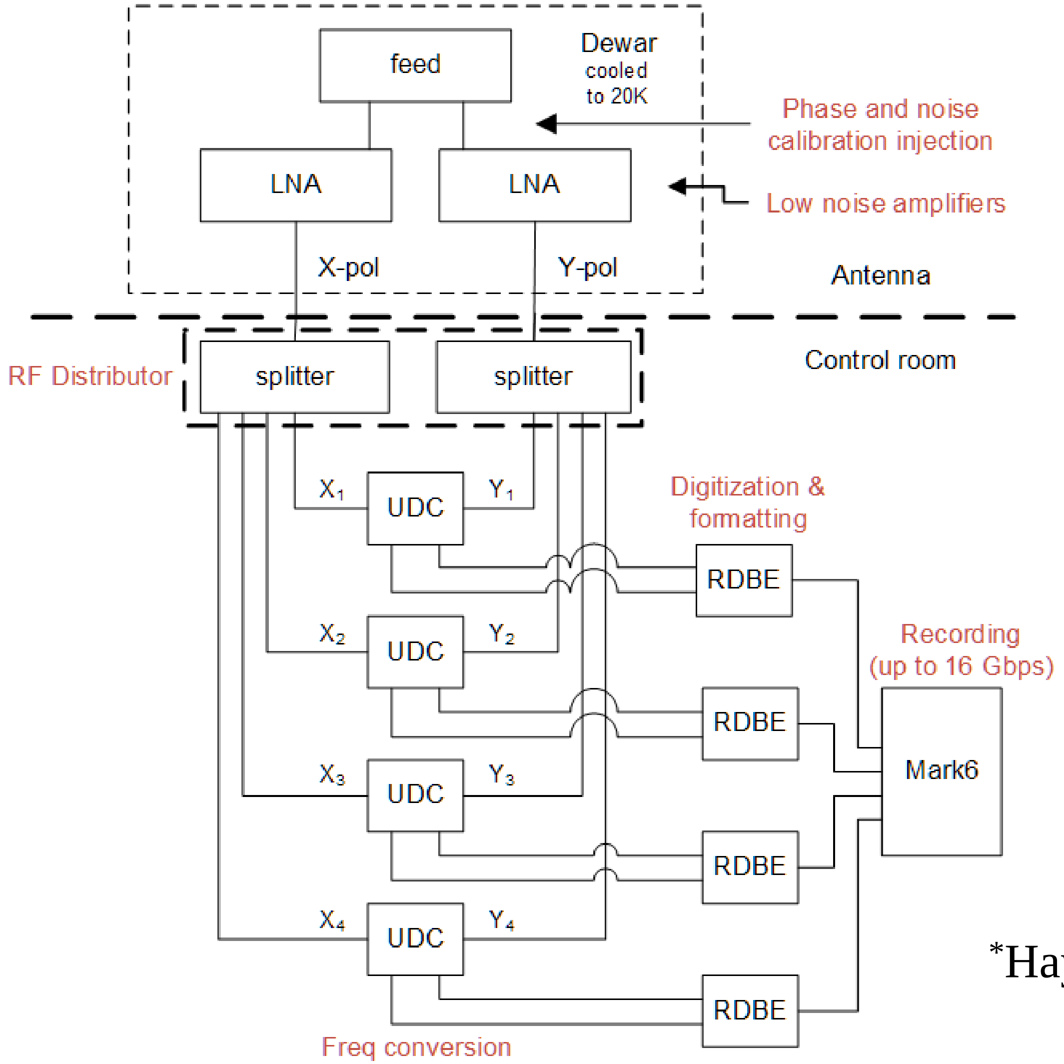
Observing Frequency Bands



S/X – Broadband Differences

Characteristic	S/X	Broadband
Number of bands	2	4
Frequency range	2.2 - 9 GHz	2.2 -14 GHz
Data rate	0.512 Gbps	16 Gbps (8 now)
Polarization	single circular	dual (linear)
Backend	analogue	digital
Antennas	large/slow	smaller/fast

Broadband System Diagram*



*Haystack implementation

MIT Haystack / NASA Implementation

- Prototype systems
  - 12-meter Patriot antenna at GGAO and 18-meter Westford antenna at Haystack
    - QRFH feed and two Caltech LNAs
    - Separate low- and high-band RF downlinks for each polarization
    - Four RDBE-G digital backends
    - One Mark6 recorder

Patriot 12M Antenna @ GGAO

Broadband observing - 1

- **Geodetic VLBI session procedures**
  - Schedule (*sked*)
  - Observe
  - Correlate
  - *fourfit*
  - *calc/nuSolve*
- Highlight differences for Broadband

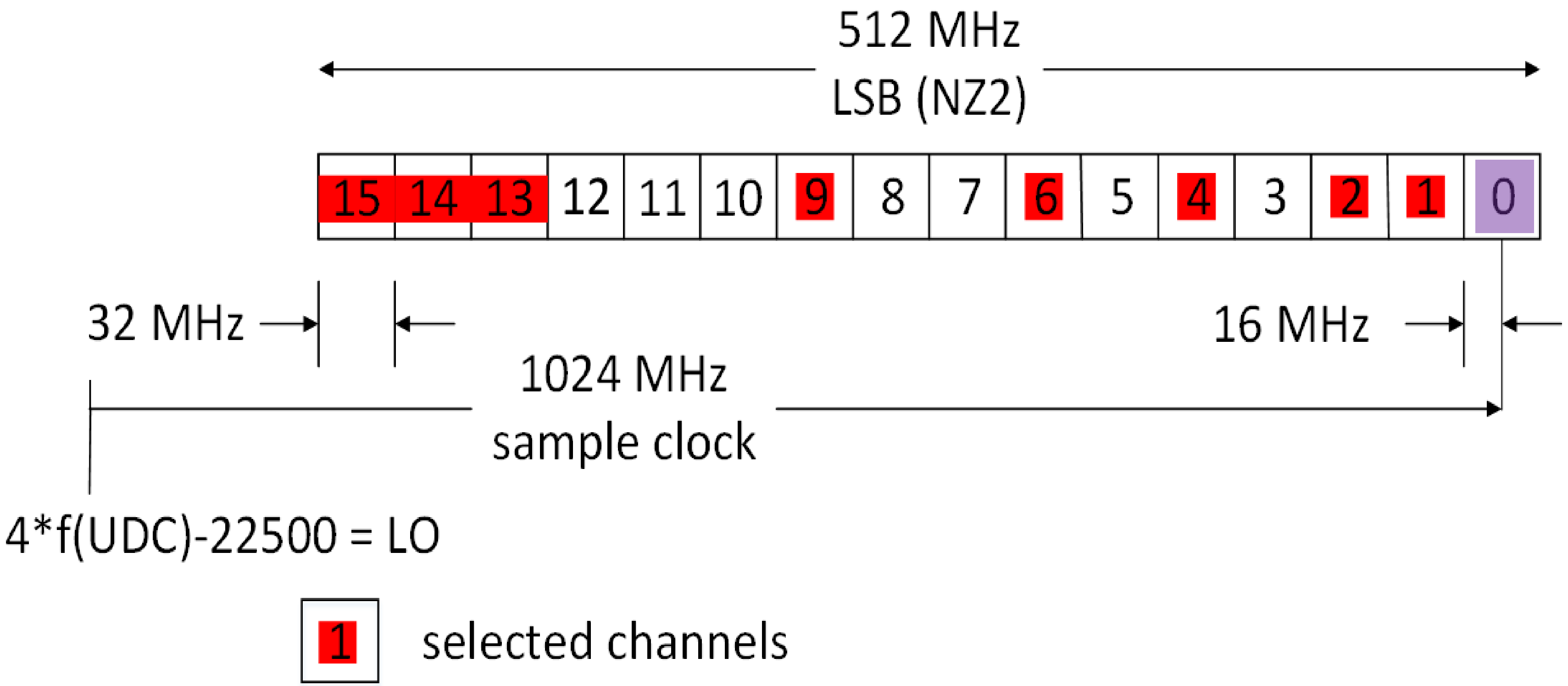
Broadband observing - 2

- Schedule (*sked*)
  - New broadband section added to allow for Mark6 recording
    - 8 Gbps onto single module
    - Buffering time of about scan length required
  - Modify input parameters to compensate for high data rate in each band
  - Use S-band and X-band flux densities but 3GHz and 10GHz system characteristics to calculate minimum scan lengths

Broadband observing - 3

- **Data acquisition format**
  - Four bands with two polarizations each band
    - Total data rate 2 Gbps per band (1 Gbps per polarization)
    - Only 15 good channels per pol'n for polyphase filter bank (PFB) but get 16 channels per band using half of the channels in each band.
    - See next figure
      - Layout for 16*32MHz recording
      - Minimum redundancy frequence per band

Frequence
(frequency sequence)



Broadband correlation - 1

- **Correlation procedures**
  - *gather* Mark6 data from raw format to linux files
  - Correlate all four bands simultaneously (soon) (or each band separately and then *fourmer* into one file)
  - Correlate HH/VV/HV/VH within each band

Broadband correlation - 2

- **Correlation procedures (cont'd)**
  - Extract all phase cal tones for every channel in both polarizations
    - Six or seven tones for each channel
    - Use all non-corrupted tones for multitone phase cal **delay and phase** for each channel (exclude tones with spurious signals)
  - Run *difx2mk4* on correlator output files to allow additional processing with the standard HOPS package (as used for S/X geodesy)

fourfit differences between broadband and S/X

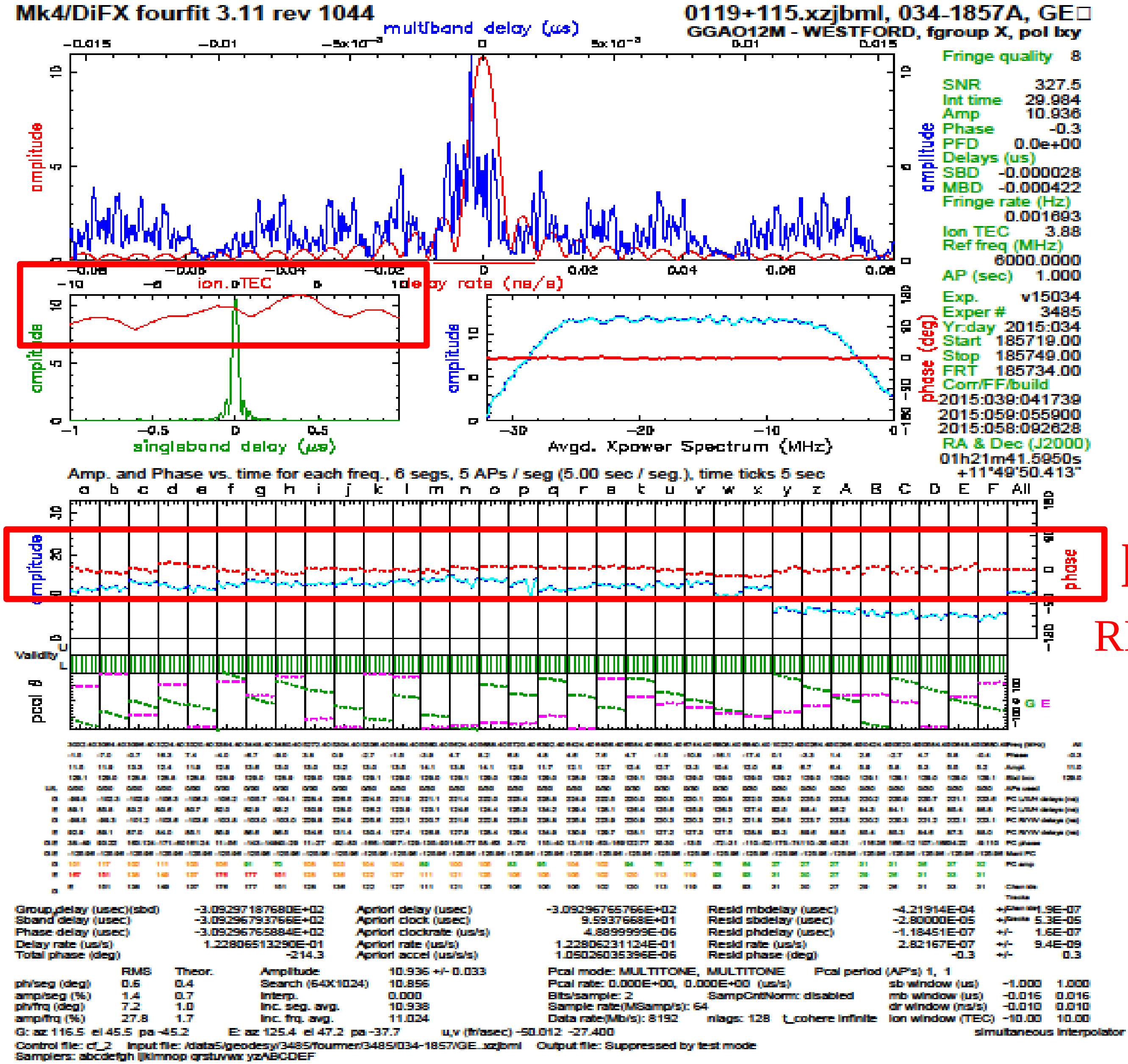
- **Phase cal**
  - Multitone pcal is now default so not different for broadband, but it is required for aligning the four bands.
  - Must account for round-trip cable delay to less than about one quarter of the multitone delay ambiguity (1/4 * 200 nsec for 5 MHz spacing): therefore input *a priori* cable delay for each station.
- **Uncalibrated delay and phase offsets between polarizations**
  - Correct for RF path length through the feed and before phase cal injection.

Post-correlation analysis - 1

- ***fourfit* (assume 64-ch correlation)**
  - Use all four polarization products to determine delay and phase differences between polarizations for each antenna
    - *fourfit* one or more strong sources for HH and VV to determine dTEC
    - *fourfit* HV and VH at that dTEC to get delay and phase differences between polarizations for each antenna
    - *fourfit* all 128 channels (4 bands * 8 channels * 4 pol'n products) to estimate group delay and consistent total electron content difference (dTEC) between the sites
  - Example *fourfit* plot in next slide

Combined polarization data

dTEC



phase

RMS 7.2°

Post-correlation analysis - 2

- ***calc/nuSolve***
  - Create database
  - (Currently) use nuSolve for preliminary analysis
    - Single time interval for full session
    - Estimate:
      - Position of GGAO (Westford fixed)
      - Clock offset at GGAO (plus second order polyn)
      - ZWD at one site (since baseline is so short)
      - Troposphere gradient at both sites

Recent observations - 1

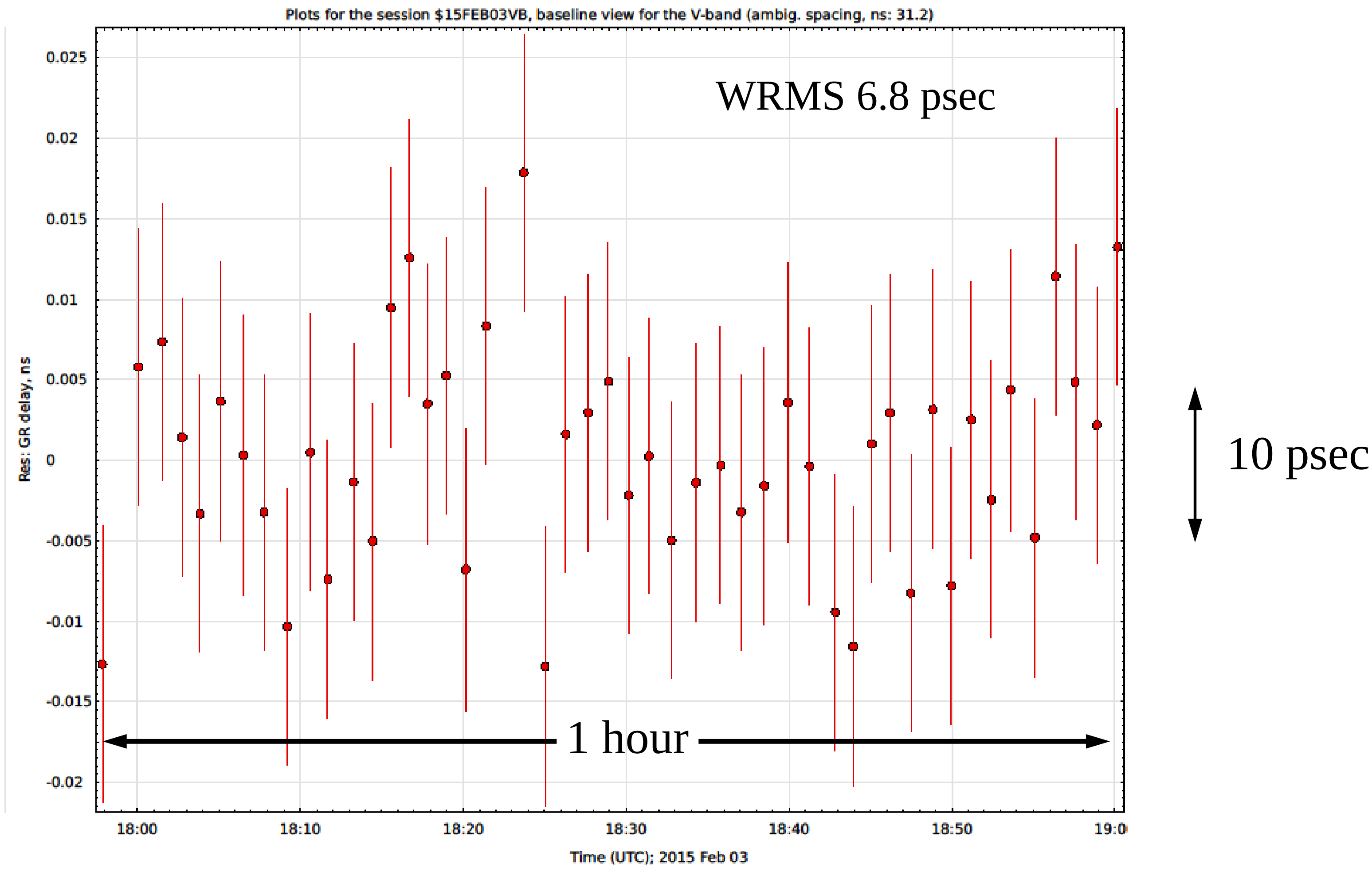
- **VGOS Data Series**
  - Work towards operational broadband observing.
  - Have observed one hour sessions about every two weeks since 2014 December (7 successful sessions).
  - The most recent sessions have been run under Field System control, including UDCs, RDBEs, and Mark6.
  - Center frequencies for the four bands:

    3.3 GHz   5.5 GHz   6.6 GHz   10.5 GHz

Recent observations - 2

- **VGOS Data Series (cont'd)**
  - Median delay uncertainty per scan is ~1 psec.
  - Correction for phase variation across the bands and with time would raise this to a few psec (see previous 64-channel *fourfit* figure).
  - With re-weighting by additive delay to the geodetic estimation, the WRMS post-fit delay residual is typically 6 psec (compared to a few times 10 psec for current S/X sessions using ~20-meter antennas).

Post-fit delay residuals V15034 2014FEB03 48/50 obs retained



Recent observations - 3

- **VGOS Data Series (cont'd)**
  - Baseline length is 601 km.
  - For six sessions, the position uncertainties for GGAO with 1 to 1.5 hours of data are:
    - Up/East/North (UEN): 3-7 mm, 1-2 mm, 1-2 mm
    - Length: 1-2 mm
  - The RMS scatters in components and length are approximately :
    - UEN: 4 mm, 2 mm, 2 mm
    - Length: 1 mm

Yet to do or understand (partial)

- **Instrumentation**
  - Add cable delay measurement systems.
  - Upgrade UDCs to Kokee version.
  - What causes freq. dependent phase distortion?
- **Analysis/understanding**
  - How should the broadband delay uncertainty be determined for input to estimation?
  - How can sky coverage be improved in scheduling programs?
  - What is the best way to determine the polarization delay and phase offsets?

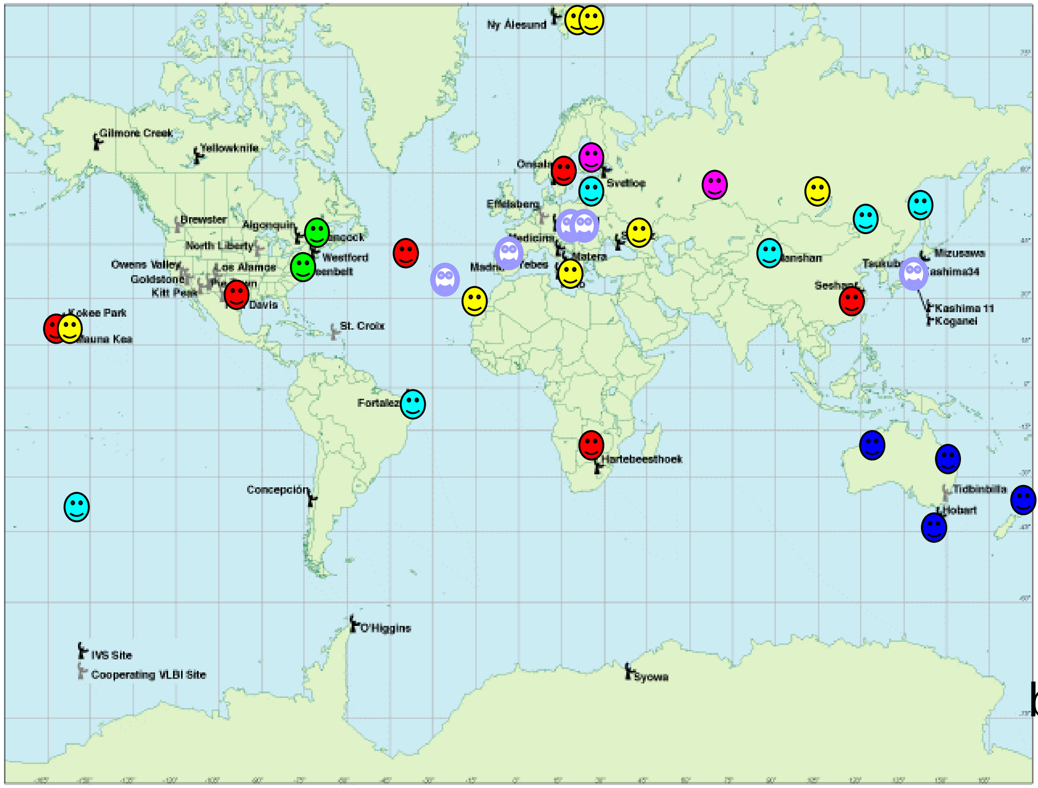
VGOS network evolution

- What are the prospects for full VGOS network?
  - Only one pair of antennas is doing Broadband VLBI.
  - VGOS-potential antennas operating but not yet Broadband:
    - Auscope (3)
    - Ishioka
    - New Zealand
    - Russia network (3)?
    - Santa María (Açores) (almost operating)
    - Wettzell (2)
    - Yebes
    - (Who did I miss?)

VGOS World

update needed!

New VGOS radio telescopes for IVS



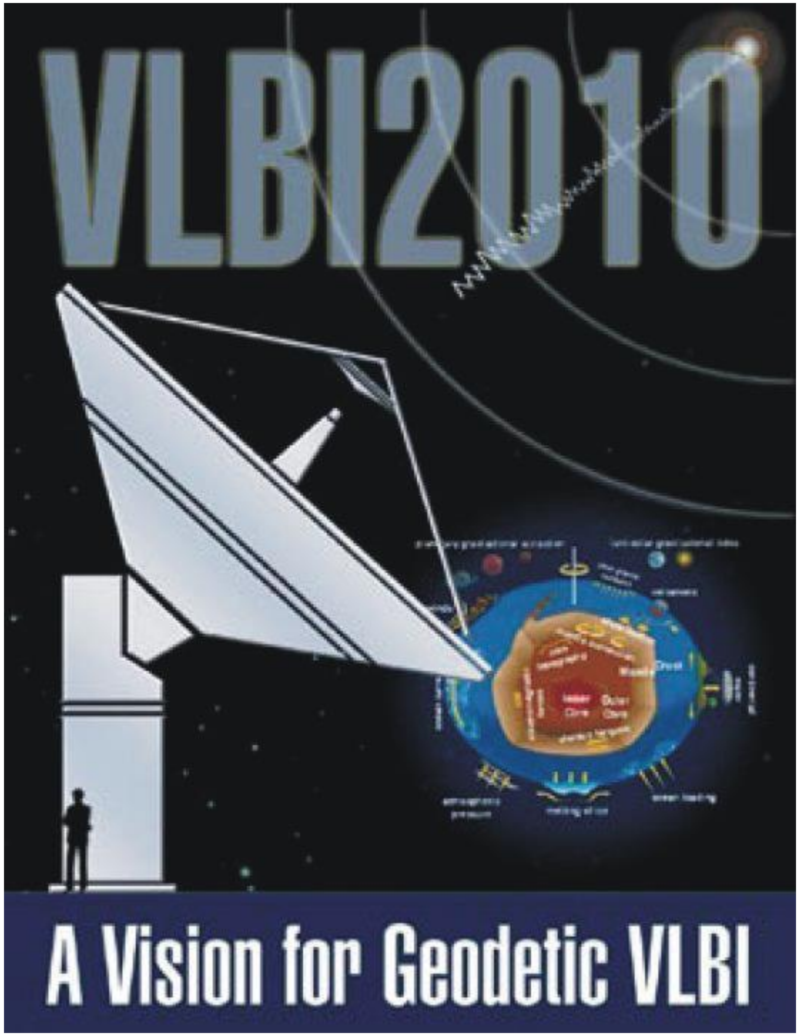
Broadband capable

- operational broadband
- under construction
- funded
- proposal submitted
- planning phase
- planning phase upgrade
- operational S/X/Ka

based on information available February 2014

original from Hayo Hase

Better late than never!



To do:

Timing figure for 5MHz/downlink

cable delay

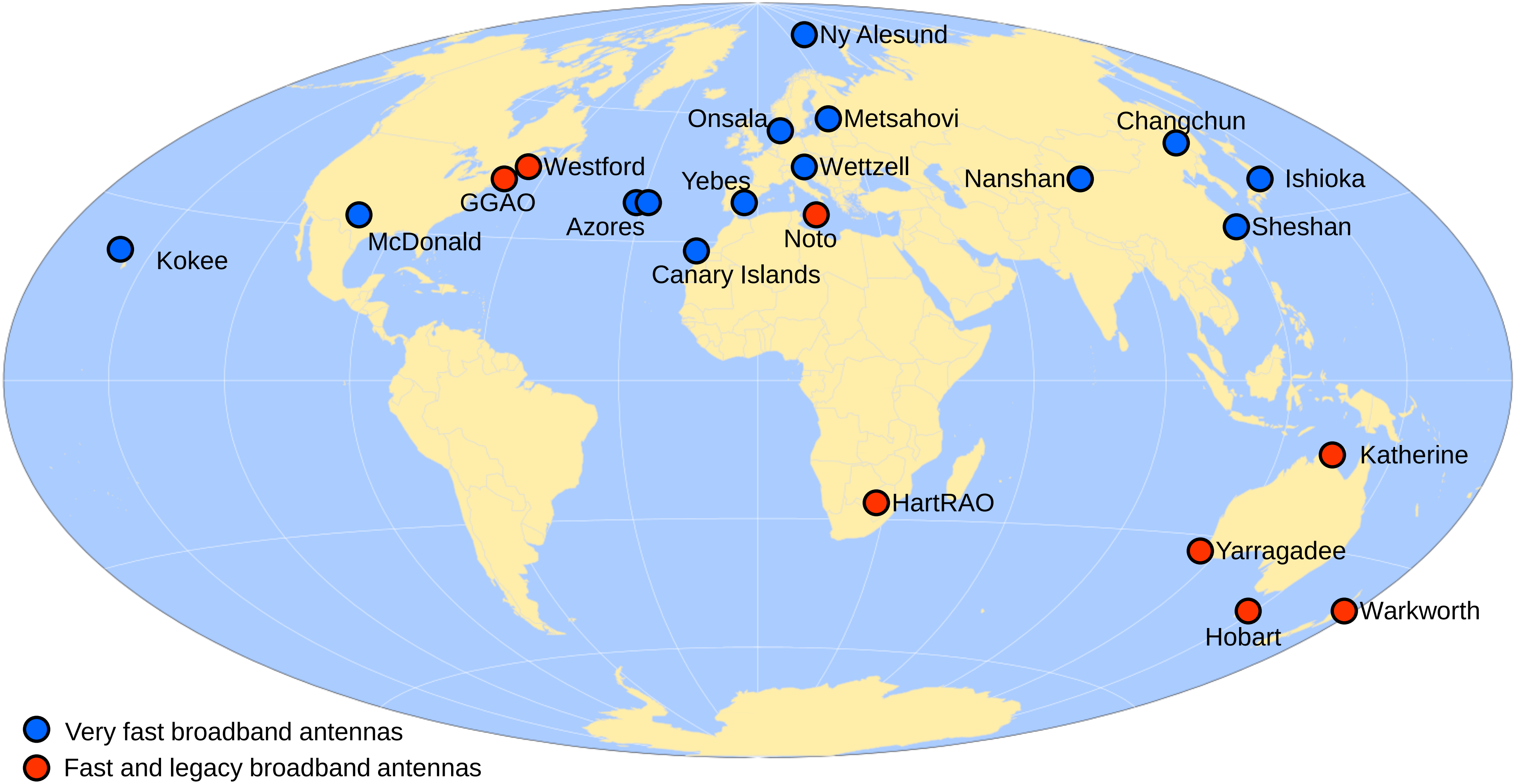
Polarization delay offset figure

VLBI2010 Recommendations

- 1-mm position accuracy on global scales
- Continuous measurements for time series of station positions and Earth orientation parameters
- Turnaround time to initial geodetic results of less than 24 hours

VGOS Network anticipated for 2017

Strong in the North Polar Region
Weaker in the Americas and Pacific Region



Courtesy Bill Petrachenko